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Introducing a commute-energy performance index for Flanders

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ABSTRACT

Based on 2001-census data for Belgium, energy consumption levels for commuting were calculated and mapped on the basis of residential locations in the administrative regions of Flanders and Brussels. Comparison with regional differentiations in commuting distances, modal shares of non-car travel modes and aspects of infrastructure and population densities clarifies some relationships between energy consumption, commuting behaviour and spatial-economic structure in the suburbanised historic–polycentric spatial structure which characterises the northern part of Belgium. It is found that mode choice appears to be of little impact for the energy performance of home-to-work travel on the scale of the Flanders region. At the other hand, proximity between home and work locations is paramount.

Residential density plays a part in this, although much depends on the specific situation. This is also the case for the accessibility of the main road and rail network. In some regions these infrastructures induce long-distance commuting, whereas in the economic core areas this effect is much less pronounced. All these are factors that are very much determined by infrastructural and spatial policies of the past.

1. Introduction

Following Newman and Kenworthy (1989), many researchers have put forward the energy efficiency of urban transport as a sustainability indicator. Although Newman and Kenworthy (1989) were repeatedly criticized because of methodological reasons, the rationale for the use of energy performance as an indicator for measuring the sustainability of transport in relation to spatial structure kept upright.

This paper investigates the link between spatial structure and energy consumption for home-to-work travel. To this end the concept of a commute-energy performance (CEP) index will be developed and tested for Flanders (Belgium). This indicator is not only considered as a proxy for the sustainability of the transport system in itself, but by extension for those of the spatial-economic structure as a whole. The results can constitute a basis for further research, which aims to determine the robustness of spatial structures in a climate of incipient fuel scarcity. A better understanding of this matter will uncover social and spatial evolutions, and leads to a policy that facilitates a more sustainable development.

The paper is structured as follows. In Section 2, we briefly discuss the relationship between energy use and spatial structure in order to conceptualize our CEP index. Section 3 puts the home-to-work commute in the context of all personal travel. The CEP index is then formally developed in Section 4. In Section 5, we introduce our data and geographical setting and discuss some spatial differentiations. For this purpose, we map the average energy consumption for home-to-work travel in Flanders and Brussels. Based on obvious regional differences, a number of hypothetical relationships with the underlying spatial and economic structures can be put forward. Finally, in Sections 6 and 7, we summarize our main findings.

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2. Energy use and urban spatial structure

The main thesis of Newman and Kenworthy (1989, 1999) is the existence of an inverse relationship between urban density and energy consumption for transport. Their research was based on data from 32 world cities. In a critical reaction to Newman and Kenworthy's (1999) conclusions, based on a new analysis of the same data, Mindali et al. (2004) argue that the assumed general correlation between density and energy consumption for transport is in fact only valid for certain aspects of the urban structure, i.e. in the central business district. Banister (1992) and Banister and Banister (1995) applied a similar methodology as Newman and Kenworthy (1989) on British cities, using data from the National Travel Survey (1985–1986) and the 1981 census. For London, the city with the highest overall density, the analysis does not support Newman and Kenworthy's thesis: energy consumption per capita is slightly higher in the capital than the average in the other surveyed cities (>25,000 inhabitants). Dodson and Sipe (2008) on the other hand introduced the concept of an "oil vulnerability index" as a quantification of the robustness of a spatial entity to rising oil prices, and also take social factors (such as income) into account. They found that those parts of the outer urban fringe where no public rail transport is available, are the most vulnerable.

It is also our aim to develop a spatial sustainability indicator that enables the mapping of regional and urban differences in energy consumption for transport. There are two important arguments that can be put forward to develop such an index. First, there is the growing importance of the energy factor in the public debate. The sharp fluctuations in oil prices, the debate about peak oil and the efforts made to reduce emissions of greenhouse gases play a role in this discussion (Witze, 2007). Second, the relationship between spatial structure and travel is a vexed issue. Travel patterns are highly heterogeneous, and vary with the morphology and the use of the space. Although concepts such as high density and diversity are classically considered characteristics of a spatial structure with a high potential for sustainable trips (Cervero and Kockelman, 1997), it is in fact very difficult to isolate spatial parameters and to demonstrate causal relationships (Van de Coevering and Schwanen, 2006; Van Acker et al., 2007; Hammadou et al., 2008). Existing literature envisages almost always clearly demarcated urban areas. Newman and Kenworthy (1989) for example, did not consider external flows, while in some of the cities they studied a significant proportion of the jobs are filled by commuters. Cervero and Kockelman (1997) and Schwanen and Mokhtarian (2005) studied the San Francisco Bay Area, which is morphologically much more homogeneous and extensive than, for example, an average European urban area. Little is known however about the relationship between the suburbanised historic–polycentric spatial structure which characterises densely populated European regions such as Flanders, and the travel patterns of its users. Moreover, travel behaviour is to a large extent determinant for the energy consumption, distances and used transport mode being the main parameter. In addition, the rate of car ownership and – for car owners – the chosen type of car play their part (Keppens, 2006). Hence, it is worthwhile to investigate the spatial differentiation in energy consumption for transport in spatially highly heterogeneous areas. The indicator to be developed should be able to make explicit the relationship with spatial qualities, such as density, characteristics of proximity or remoteness, or the presence or absence of major transport infrastructure at different geographical scales.

3. Limitations of studying the home-to-work commute

Accurate data on the home-to-work commute is more often available than data on other trips. This is probably the main reason why many studies, such as those of Dodson and Sipe (2008), focus on home-to-work travel to quantify the sustainability of travel patterns. However, in studies focusing on a small enclosed area, it is easier to incorporate different kinds of trips, as was done by Saunders et al. (2008).

This paper too is based on home-to-work commuting data. This commute is not representative of all trips, but does affect significantly non-work related trips. From the theory of the constant travel time budget (Schafer, 2000), we can say that commuters who spend a lot of time travelling to work will spend less time on other trips. This means that they will make more efficient chained trips and that they will look for destinations closer to home, but also that they will choose more frequently for fast means of transport (i.e. the car). Moreover, the home-to-work commute is more inert than other trips are, which can be illustrated on the basis of price elasticities (Mayeres, 2000). Given this rigidity, changes in preconditions, such as fluctuations in fuel prices, will be more problematic for commuting patterns than for non-work trips. Furthermore, commuting trips cover more often large distances (Zwerts and Nuyts, 2004), and thus contribute significantly to the negative effects of traffic. The last two arguments indicate that the study of the home-to-work commute remains very important.

It is important to understand that the rigidity of the commute, both with respect to distance covered and with respect to modal choice, is not only a spatial issue. The attitude of the commuter towards the destination and itinerary, and in particular its habits, determine this rigidity to a large extent. Consequently, we should consider the travel pattern as a result of the interaction between space, motivation and habit (Gardner, 2009).

4. Commute-energy performance (CEP) index

In order to exemplify the relationship between the spatial configuration of an urban region and energy use we develop a commute-energy performance (CEP) index. This index is obtained by dividing the total amount of energy consumption for home-to-work travel per census block (i.e. the smallest geographical research unit) by the working population (active workforce) that lives in the census block. More formally

$$\mathrm{CEP}_s = \frac{D_s \cdot \sum_i \bar{E}_i \cdot c_{i,s}}{N_s}$$

In which CEP_s is the energy performance per member of the active workforce for home-to-work travel from the considered (statistical) census block s; D_s is the total distance travelled (one way) for home-to-work travel from the considered census block s; $\bar{E}_i$ is the mean energy consumption per passenger for the considered mode i; $c_{i,s}$ is the correction factor for the considered mode i, within the census block s; N_s is the number of members of the active workforce in the considered census block s.

In order to take into account the differences in energy efficiency between the different transport modes used, the home-to-work travel trips are split up into motorized (fuel consuming) trips (car, public transport) and non-motorized trips (on foot, bicycle). For public transport there are significant differences in energy efficiency between bus, tram, metro, and train. Hence, we formulate the mean energy consumption per passenger in relation to the type of public transport used

$$\bar{E}_{btm} = \sum K_i \cdot \bar{E}_i$$

In which $\bar{E}_i$ = mean energy consumption per passenger for the considered mode i (bus, tram, metro); K_i is the share of the considered mode i (bus, tram, metro) in the total number of kilometres made by these three modes.

For the train mode we can further distinguish between electric and diesel trains (where α denotes the fraction of electric/diesel trains), resulting in

$$\bar{E}_{tr} = \alpha \cdot \bar{E}_{tre} + (1-\alpha) \cdot \bar{E}_{trd}$$

For car use a comparable subdivision in view of the type of combustion fuel used (petrol, diesel, LPG) should be made as well. However, our commuting data (see further) does not allow to distinguish between different types of car trips, so although further subdividing $\bar{E}_i$ is useful, it will not add to the analysis. For all non-motorized trips $\bar{E}_i$ is of course equal to zero.

To keep the relationship between the mode and the distance travelled, for each mode a correction factor is derived from the average trip length

$$c_{m,s} = \frac{S_{m,s} \cdot \bar{D}_m}{\sum_i S_{i,s} \cdot \bar{D}_i}$$

In which $c_{m,s}$ is the correction factor for the considered mode m, within the census block s; $S_{m,s}$ is the share of the considered mode m as main transport mode in the total number of home-to-work trips from the considered census block s; $\bar{D}_m$ is the mean distance of a home-to-work trip with the considered mode m; i is each of the considered modes.

Finally the resulting number of person kilometres per mode is multiplied with a standardized value for the energy consumption per mode.

5. Geographical setting and data analysis

Our developed CEP index is tested for Flanders and the Brussels-capital region. Map 1 is a schematic representation of the spatial structure of Flanders, as defined in the Spatial Structure Plan for Flanders (Ruimtelijk Structuurplan Vlaanderen (RSV), 1997/2004). The RSV is the overarching spatial policy plan for the Flanders region. The RSV selects three "metropolitan areas", with more than 300,000 inhabitants, being Ghent, Antwerp and the Flemish urban area around Brussels. Because of the consistency of the research, we also integrate the Brussels-capital region.

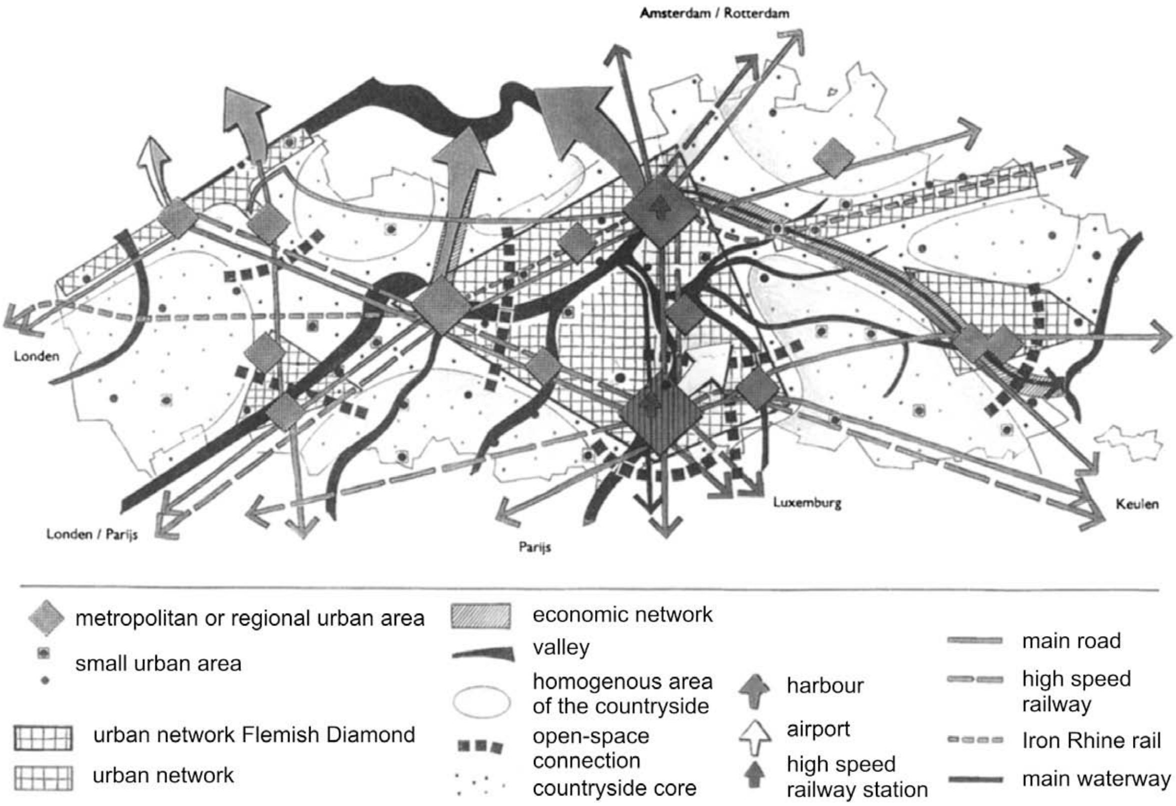
Furthermore the RSV selects ten "regional urban areas" with a magnitude which is situated between 50,000 and 150,000 inhabitants, as well as five "urban networks", an "economic network" along the Albert canal and five "gates" (ports and airports). The main urban network is that of the Flemish Diamond, which is bounded by the three metropolitan areas and the regional urban area of Leuven, and is the economic core of Flanders. The other areas are considered as countryside, still including a number of small urban areas and economic nodes with rather limited development perspectives.

Also within the infrastructure network, especially the road network, a selection and classification of roads is made. The metropolitan and regional urban areas are all opened up by the main road network, and served by at least one train station.

The data used to calculate the CEP index for Flanders and Brussels are drawn from various sources. The so-called General Socio-Economic Survey 2001 (SEE 2001, see: Verhetsel et al., 2007) is a comprehensive survey of the Belgian population (excluding children younger than six years old), which has its origin in the 10-yearly census. The response to the survey is 95%. The questionnaire of SEE 2001 contains a number of mobility related questions. The distance between home and work or school is assessed. In addition, questions are raised about the means of transport used for home-to-work or home-to-school trips, the number of daily trips whether or not combined, car ownership and the perception of the supply of public transport around.

Data on the average trip length per mode is based on the Travel Behaviour Research project in Flanders (OVG 2001) (Zwerts and Nuyts, 2004) (Table 1).

The standardized values for the energy consumption per mode are taken from De Vlieger et al. (2006), and are based on the French research by Enerdata (2004) (Table 3). All energy values are converted to kilowatt hour per person kilometre (kWh/pkm). In each case the final energy consumption by the vehicle is considered, meaning that for electric vehicles the



Map 1. Schematic representation of the spatial vision on Flanders. Source: RSV (1997/2004).

Table 1
Average trip length for home-work travel by transport mode, for the purpose of determining the correction factor for the trip length (based on OVG 2001).

Bicycle	$\bar{D}_{bc} = 4.07$ km
Moped, motorbike	$\bar{D}_{mb} = 10.85$ km
Transportation organised by the employer or school	$\bar{D}_{em} = 18.86$ km
Car driver	$\bar{D}_{cd} = 20.33$ km
Car passenger	$\bar{D}_{cp} = 17.43$ km
Train	$\bar{D}_{tr} = 48.48$ km
Bus, tram, metro (underground)	$\bar{D}_{btm} = 18.86$ km
On foot only	$\bar{D}_{of} = 2.15$ km

Table 2
Itemization of passenger kilometre share for urban and regional public transport by mode, Flanders and Brussels.

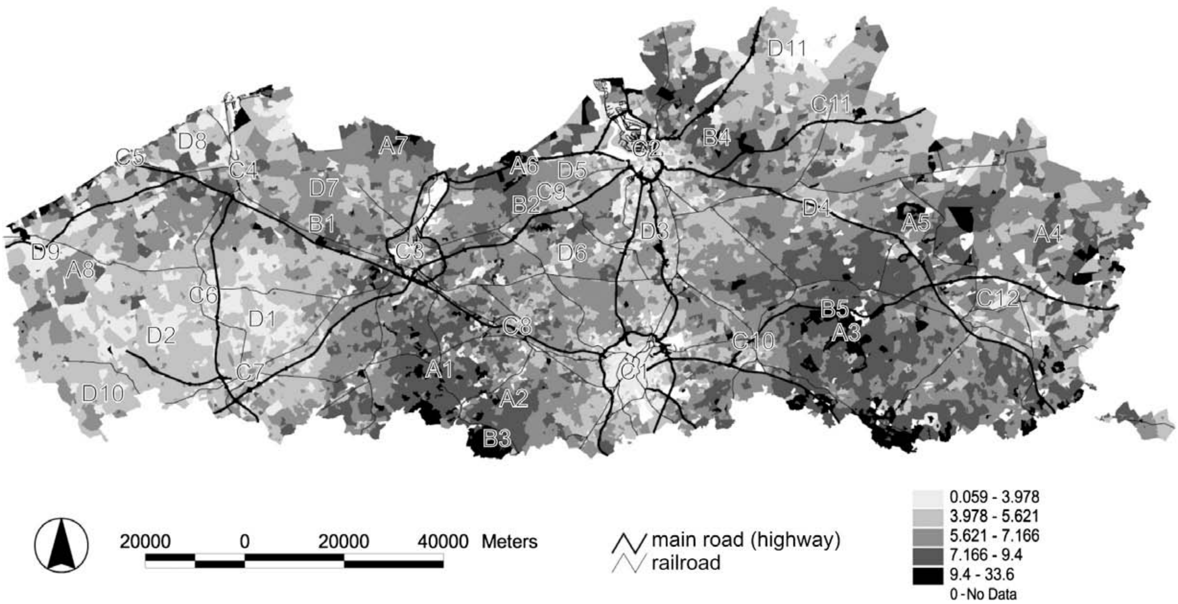
Tram and trolley bus	$\bar{K}_t = 11.3\%$
Metro (underground)	$\bar{K}_{me} = 2.0\%$
Bus	$\bar{K}_b = 86.7\%$

losses that occur in the production and transmission of the electricity, which depend greatly on how it is generated, are not taken into account. For the category "car as passenger" the same value is applied as for the category "car driver", since the default value is set per person and already takes into account the average occupancy rate of the vehicle. More specific variations in energy consumption, such as the distinction between diesel and gasoline cars, or regional differences in the composition of the fleet of personal cars or the ridership of buses and trains, are not taken into account.

Data on the use of local public transport was split up on the basis of the passenger statistics of the urban and regional public transport companies in Flanders (De Lijn) and Brussels (STIB) for the year 2006 (De Lijn, 2006; Maatschappij voor het Intercommunaal Vervoer te Brussel, 2006) (Table 2). The mode train is itemized into 78% electric and 22% diesel, based on De Vlieger et al. (2006).

Table 3
Default values for energy consumption per person kilometre (source: De Vlieger et al. (2006)).

Tram	$\bar{E}_t = 0.06$ kWh/pkm
Metro (underground)	$\bar{E}_{me} = 0.08$ kWh/pkm
City bus	$\bar{E}_{cb} = 0.25$ kWh/pkm
Coach	$\bar{E}_{co} = 0.32$ kWh/pkm
Aggregated: urban and regional public transport	$\bar{E}_{btm} = 0.26$ kWh/pkm
Electric train	$\bar{E}_{tre} = 0.13$ kWh/pkm
Diesel train	$\bar{E}_{trd} = 0.18$ kWh/pkm
Aggregated: train	$\bar{E}_{tr} = 0.14$ kWh/pkm
City car	$\bar{E}_{cc} = 0.43$ kWh/pkm
Family car	$\bar{E}_{cf} = 0.53$ kWh/pkm
Aggregated: car	$\bar{E}_c = 0.48$ kWh/pkm
Bicycle, on foot	$\bar{E}_{bc}, \bar{E}_{of} = 0.00$ kWh/pkm



Map 2. Daily energy consumption per capita for home-work travel (kWh). Source: SEE 2001.

6. Results

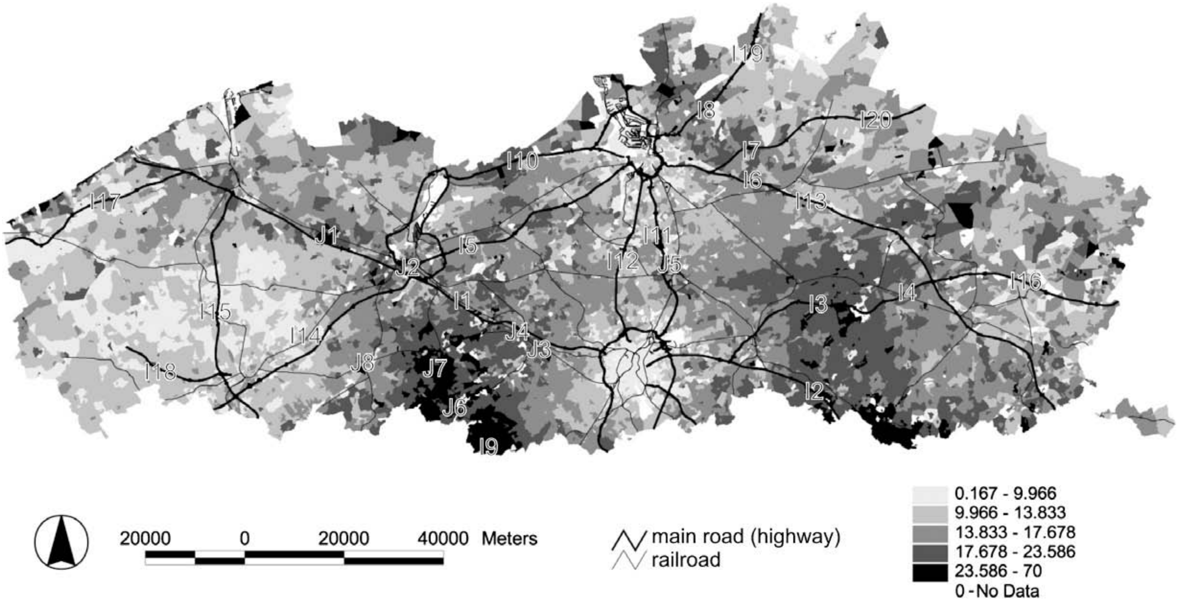
6.1. Spatial distribution of the CEP index: a first glance

We calculate the CEP index for home-to-work travel, based on the departure zones. Because of the limitations of the available data, the resulting map should only be interpreted as an approximation, which aims to uncover the gradients with regard to energy consumption for home-to-work travel in Flanders and Brussels. In a next step the relationship with a number of spatial characteristics will be unveiled (see further).

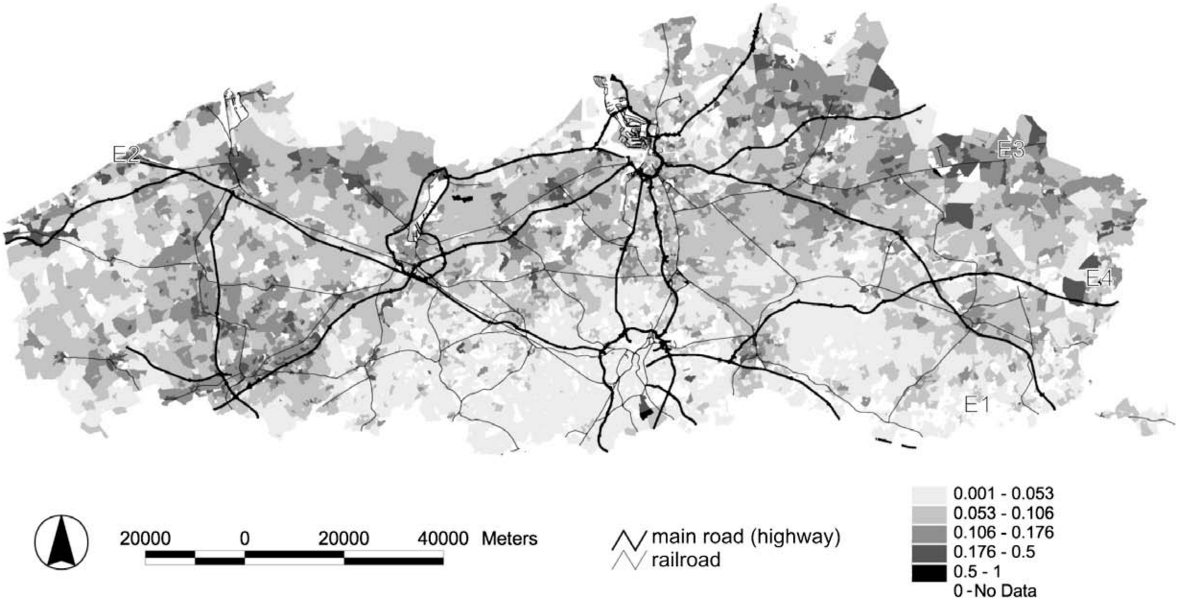
In order to interpret the CEP index, the relevant spatial characteristics are mapped as well, based on data from SEE 2001. The main road network and the railways are added to all maps. Map 3 shows the average home-to-work distance per member of the active work force. For this, data on home-to-work distances are aggregated for each neighbourhood (census block) and divided by the working population. It is possible to draw up a similar map for the home-to-school distances. Maps 4–6 present the frequency with which the modes, that are known to be energy-efficient, are used as main transport mode for home-to-work trips. For the purpose of ease of interpretation, these maps are simplified in the sense that, for example, any pre- and post-transportation is not considered while evaluating the use of the various modes. Moreover, not all modes are included: pedestrians, car passengers and transport which is organised by the employer are not incorporated in the set. The purpose of the maps is thus to give a global overview of the variation of these parameters on the territory of Flanders and Brussels.

According to the mapped CEP index, energy consumption for home-to-work travel seems to be particularly high in those regions which in spatial planning terminology are defined as the countryside (A1–8) (Map 2).[1] These regions have in com-

[1] The applied codes refer to the respective zones on Maps 2–5.



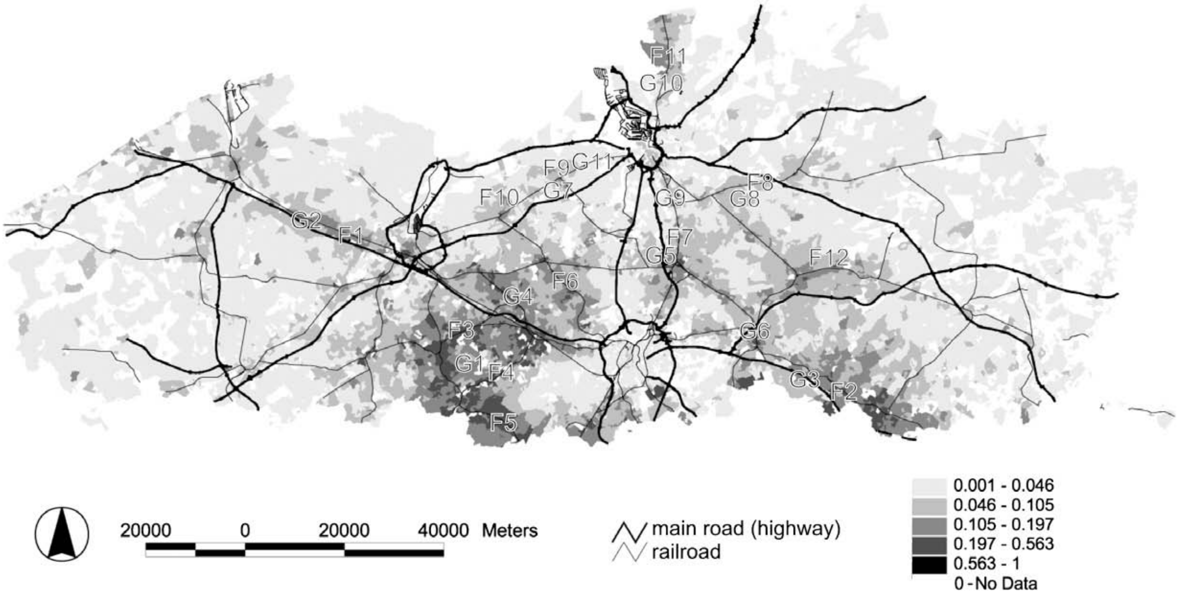
Map 3. Mean distance for home-work travel (km). Source: SEE 2001.



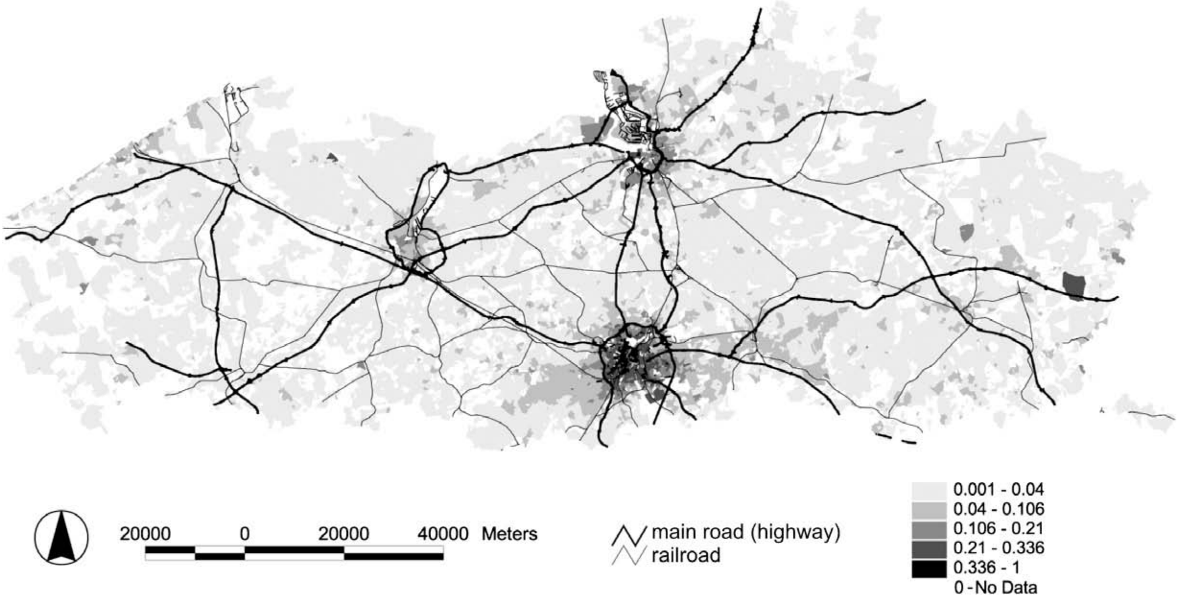
Map 4. Share of bicycle in home-work trips. Source: SEE 2001.

mon that they possess a relatively rural character, compared to the labour markets where they are focused on. The regions A1 and A3, for example, are influenced by the labour markets in the metropolitan and urban areas of Brussels, Ghent and Leuven, even if those are relatively distant (Van Nuffel, 2007). In addition, commuters in these rural regions have on average higher incomes which allows them to live outside the city centres in the relatively quiet and green environments, being less sensitive to the financial impact of the large daily commuting distances.

Apart from that, some corridors along the motorways are strongly reflected in the map. The locations B1–4 catch the eye. It is clear that in these cases the increased accessibility by the presence of a motorway has contributed to enlarge commuting distances and the increased importance of the car as a transport mode. The area, in which the energy consumption is pre-eminently low, is the Brussels-capital region (C1). The Flemish urban area around Brussels has a more or less comparable pattern, but still scores worse than the Brussels' municipalities. This result concurs with what might be expected, as the Brussels region represents the largest job market of the country, and also has the highest population densities. It is therefore consistent with the idea that the match in the labour market supply and demand is achieved within short distances. More-



Map 5. Share of train in home-work trips. Source: SEE 2001.



Map 6. Share of bus, tram, metro in home-work trips. Source: SEE 2001.

over, the metropolitan spatial structure is responsible for the relatively large influence of other parameters on the energy consumption, such as modal split and vehicle ownership. This will be discussed below.

Similar patterns occur in the two other metropolitan areas of Antwerp (C2) and Ghent (C3), in which the effect of the metropolitan structure of Antwerp clearly outreaches the case of Ghent. In all regional urban areas, we also find lower energy consumption than the average. But also outside the metropolitan and regional urban areas, there are a number of regions that come out on the right side by their significantly lower energy consumption. The most contiguous region we find at D1–2. This region is characterized by a strong sprawl of less specialized labour, and a strong spatial interweaving of the labour market with the residential structure. The importance of location-bound industries, in particular in the agricultural sector, probably plays a part in this. So, the distance between home and workplace remains relatively confined.

Furthermore, also the corridor Brussels–Mechelen–Antwerp (D3), an important transport artery, scores remarkably well on the map, as well as a part of the economic network of the Albert canal (D4). These economically strong areas have high concentrations of employment in a – on the scale of Flanders – relatively good mix with the residential structure. We see the same phenomenon, albeit on a smaller scale, arising in D5–D7.

The rural areas D8–D11 show rather low figures. Apparently, the relatively poor accessibility of these regions has caused only a few long-distance commuters to settle here. In addition, the low population and building density in these regions makes that a rather large share of the population is still working in the local agribusiness.

6.2. Spatial patterns and relation to home-to-work distance

The CEP map (Map 2) shows a remarkable resemblance with the map that visualizes the home-to-work distances (Map 3). The Pearson's correlation coefficient between the two sets of indicators is close to 0.95. We can therefore conclude that the energy consumption for home-to-work travel is first and foremost determined by the distance between home and workplace. Contrary to what is generally assumed, it appears that the used transport mode plays only a very limited role. This can partly be explained by the fact that the average distance covered by train commuters (on average 48 km in 2000) is much larger than the average journey that is made by car (on average 20 km). Secondly, the bicycle is only an alternative for short trips, which makes this mode only marginally represented in the total number of kilometres.

6.3. Relation to the use of the bicycle

In Belgium, particularly in Flanders, the bicycle has always been an important means of transport in short distance commuting. Belgium is ranked third in Europe (after The Netherlands and Denmark (1997)) with regard to the use of the bicycle (Witlox and Tindemans, 2004). This is chiefly explained by the flat topography, as well as the strong railway-bounded prewar spatial development (in which the bicycle appeared to be the perfect pre- and post-transportation means). The relief shows an unmistakable determining factor with respect to the use of the bicycle in home-to-work travel. The cycling map (Map 4) has therefore bright spots in the hilly regions A1, A2, A3, D10 and E1. Also, in the Brussels-capital region and the Flemish urban area around Brussels, cycling to work hardly occurs. The very dense traffic during peak-hours is an important explanatory variable.

In all regional urban areas, the bike is still very important in the home-to-work travel. That is also the case, albeit somewhat less explicit, in the metropolitan areas of Antwerp and Ghent. Furthermore those regions where a significant mix of living and working occurs, and the distances are accordingly short, catch the eye (D1–7). In addition, there are some more isolated areas that also score well in terms of bicycle use, such as the urban network of the coast (E2) and the peripheral regions E3 and E4.

When looking at the cycling map (Map 4) and the distance map (Map 3) at one glance, we see that the largest share of cyclists occurs at first in those regions where the home-to-work distances are the shortest, with the Brussels-capital region and the Flemish urban area around Brussels as a major exception to this rule. According to the OVG 2001, the average length of a cycle trip in home-to-work travel amounts to 4 km. This figure is based on a survey, and its reliability as a reported distance is relatively small given the small distance range (Witlox, 2007). Clearly, the bicycle plays a major role in those regions where the commuting distances are of this small magnitude. The influence of the bicycle on the total energy consumption for home-to-work travel is very limited. Even in regions with a relatively high share, the bike use share in commuting is less than 20% of the total number of trips. As trips with other modes cover much larger distances per trip (see Table 1), the gain in terms of energy consumption made by cyclists is of little significance. The low energy consumption in areas with a high proportion of cyclists is largely on the account of the small absolute distances, regardless of the transport mode used. But the positive impact of the short distances in these areas is reinforced by the larger share of cyclists that substitutes car use on short distances, in comparison with other regions.

6.4. Relation to the use of the train

Maps 5 and 6 visualize the level of use of public transport. Map 5 deals with the share of train passengers, while Map 6 demonstrates the share of tram, bus and metro travellers. High concentrations of train commuters can be found along the railway axes which provide since a long time a fast connection with the capital, particularly to the west and southwest of Brussels (F1–F7). Also some railway axes that are focused on Antwerp, catch the eye (F7–8). Apart from this, some local concentrations of train commuters (F9–12) can be distinguished. The inhabitants of the Brussels-capital region and the Flemish urban area around Brussels hardly use the train for home-to-work travel. This applies in general to the regions which are relatively remote from Brussels too. In the outlying regions of Flanders, and particularly the northeast, commuters hardly use the train.

Interestingly, a significant portion of the concentrations of train commuters is located in those areas where commuting distances are the largest and corresponding energy consumption is the highest. This is particularly the case in the area southwest of Brussels (G1), and the infrastructure axes towards Ghent (G2) and Leuven (G3). This can be explained by the finding from the OVG 2001 that the average length of a home-to-work trip by train amounts to 48 km, which is very high (Table 1).

The train is therefore mainly an alternative to long car trips. Consequently, it stands to reason that the train is popular in regions with large commuting distances.

However, this does not apply to all areas where the train is well positioned. In particular, a number of regional urban areas (G4–7) and Ghent show relatively low energy consumption combined with a rather high proportion of rail commuters. This applies to a certain extent also to the railway axes that focus on Antwerp (G8–G11).

It is however not possible to make unequivocal statements about the impact of the use of the train on energy consumption. First, it is true that the average rail passenger covers larger distances than the average car driver (48 km compared with 20 km). When we multiply the average energy consumption per kilometre (0.14 kWh/pkm, respectively 0.48 kWh/pkm, see Table 3) by the average number of kilometres per mode, it appears that in home-to-work travel the energy consumption of a train trip per person is only 30% less than the energy consumption of a trip by car. This difference is less impressive than the expectations raised by the sustainable image of the train. Fast rail transport supply also induces long-distance commuting, which means no gain in terms of energy consumption. Finally, the majority of train journeys entail travel to and from the station, which often means an additional trip by car.

On the other hand, the train substitutes long car trips, at least where rail transport supply is present. Furthermore, the train is doing this – calculated per kilometre – in a more energy-efficient way. Nevertheless, the share of train commuters, even in the concentration areas, is limited to a maximum of approximately 20%. In general it may be said that there occurs only a positive impact on energy consumption by use of the train in those regions where the average home-to-work distances are already large. But the effect is still too small to be visible on the energy performance map (Map 2).

6.5. Relation to the use of urban and regional public transport

Map 6 shows that tram, metro and bus as a main transport mode in home-to-work trips only play a significant part in the three metropolitan areas. In Ghent, the smallest of these metropolitan areas, this mode scores only in a few neighbourhoods higher than 10%. In Antwerp the influence of the urban and regional transport reaches beyond that, with values that are often well above 10%. In Brussels, where urban transport is built on the backbone of the metro, the situation is completely different. Many neighbourhoods show a share of around 30%.

Given the preponderance of Brussels in the use of this mode, we cannot draw any conclusions about the average trip distance. This is because the values in Table 1 are derived from a sample survey from Flanders. The impact on energy consumption is difficult to predict. There is a significant discrepancy between the energy consumption of electric rail transport and that of (diesel) buses. Only in Brussels an extensive metro and tram network exists.

On the other hand, those parts of Brussels and Antwerp that show lower energy consumption per capita have also a high to very high proportion of public transport users. It is clear that the high density of inhabitants and jobs in those cities combines the positive effects of the proximity of functions with an energy-efficient and well exploited urban transport system. The relative good energy efficiency and the high patronage of the metro, supplemented with the tram, account for this.

In the rest of Flanders the urban and regional transport, based on diesel buses, hardly plays a part in the energy performance of home-to-work commuting. The supply, which is limited in comparison with the metropolitan areas, and the non competitive speed of this kind of public transport contributes to the limited success of the urban and regional transport in the market segment of home-to-work travel. Although we will not discuss this more profoundly, the relatively low ridership outside the urban areas also works to the detriment of the energy performance of public transport.

6.6. Relation to car ownership

Car ownership is expressed in number of available cars per household. In the historic centres of the study area, in particular those that are part of the metropolitan areas, car ownership is low. Among other things, spatial factors are at the basis of this. The high density, the significant mix of functions and good supply of public transportation makes it relatively easy to live without a car in the city centres. Also, a number of social elements play a part, since it is precisely in these areas that the family sizes are small and household revenues are rather low. However, it is difficult to isolate environmental and social factors. The environment and the rent and real estate prices in the city are often not adapted to the lifestyle of families with children. In addition, those families need more often combined trips, for which the car is usually the appropriate means of transport.

In spatial terms the zones with a remarkably high car ownership have following characteristics: they are suburban areas of major employment centres, which also have a quick access to the main road network. In social terms those are areas with high incomes. All main concentrations are located in the suburban belts around the three metropolitan and some regional urban areas.

Despite those regions that catch the eye, the regional differentiation is in fact very limited. The resulting map is fairly homogeneous. The differences are usually too small to be able to determine unique relationships between car ownership and energy consumption for home-to-work travel. However, this is possible in the above mentioned areas that attract the attention. Where the car ownership is significantly lower (the urban centres), also energy consumption is lower, and vice versa in zones where the car ownership is significantly higher (the mentioned suburban areas). In the rest of Flanders the

relationship is much less pronounced. In the urban network of cities situated along the coast, with its atypically aged demographic composition, there even seems to be an inverse relationship between car ownership and energy consumption.

7. Relation to spatial-morphological characteristics

The CEP index is also useful in interpreting the relation to a range of spatial-morphological characteristics. As an exploration, we outline the relationship between energy consumption and two notable spatial characteristics: residential density and proximity to the main road and railway network.

7.1. Relation to the population density

Density is perhaps the most widely used measure, which is also easily quantifiable. In their research about the relationship between urban density and fuel efficiency, Newman and Kenworthy (1989) included Brussels. The study area was limited to what is today called the Brussels-capital region. External commuting flows were not considered, while we know that most jobs in Brussels are taken up by people who commute. Let us now repeat the Newman and Kenworthy (1989) exercise for Flanders and Brussels based on our developed CEP. Fig. 1 plots the energy consumption for home-to-work travel on the basis of residence in relation to the population density of the block. The image is of course only a facet. Further research will also provide relations with the density of jobs on employment locations, and the focus could be expanded to all types of travel (school, shopping, recreation, visiting, etc.). Despite the limited coverage of the research field, we can see a number of interesting similarities and differences with what Newman and Kenworthy (1989) have found.

In general, it appears that the basic argument is still valid: the energy performance improves with increasing density. However, the large variation at the root of the graph catches the eye. Even though the trend line for energy consumption is rising with decreasing density, for a part of Flanders, in fact, an inverse relationship applies. The part of the dotted cloud that is situated near the root of the graph ('A') represents the rural areas (i.e. countryside). These areas are typified by sparsely populated regions with a non-intensive home-to-work travel pattern. In these areas, most people tend to work at or near their home: farmers, and local economy workers.

The part of the dotted cloud that is situated above the left part of the trend line ('B') represents the peripheral suburban sprawl. These areas have developed as a result of counter-urbanised delocalization, and are mostly inhabited by people who exhibit a strong urban lifestyle. Their professional lives are also mainly concentrated in the urban areas; hence, they represent an important travel demand.

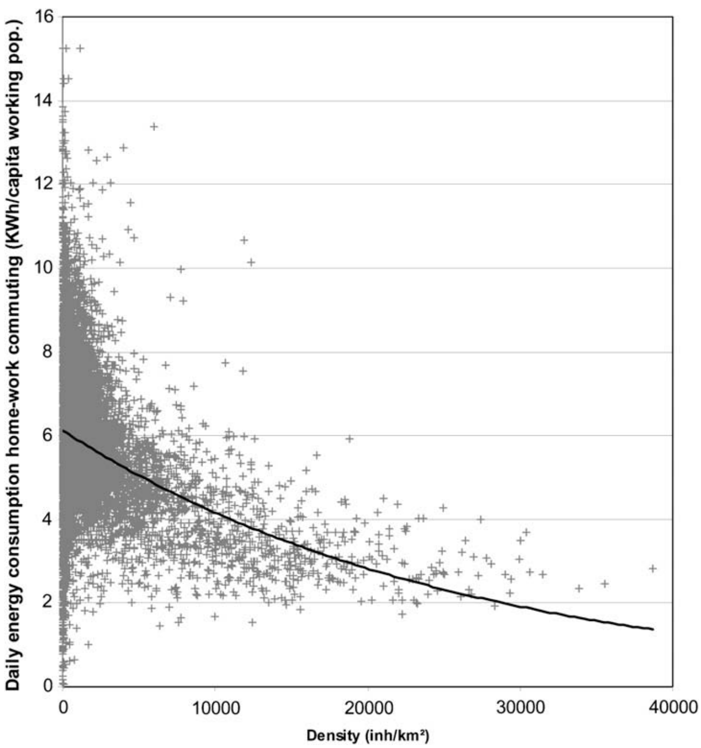


Fig. 1. Plot of residential density and energy consumption for home-work commuting, per census block.

The areas which are situated around the trend line roughly represent the urban areas. The suburban blocks that are adjacent to the traditional city centres are represented around the left part of the trend line ('C'), while the traditional city centres themselves can be found on the right side of the graph ('D'). In contrast to the analysis of Newman and Kenworthy (1989), which considered only urban areas, we can thus deduce a spatial typology from regional variations in the efficiency of the transport system.

7.2. Relation to the access to the main road network

In the analysis of the spatial variation in energy performance of home-to-work travel we already referred to a possible link with the location of the motorways. In order to gain further insight into the potential effects of the present infrastructure, the main road network and the rail network was already presented in Map 2. Interestingly, certain main roads stand out on the map, while others do not. Increased energy consumption is clearly visible in the regions I1–10. All of these cases are rural regions that became very well connected by the construction of a main road, but do not have any large or diversified employment. The new access to the main road network has encouraged moving to the countryside, has generated traffic, has increased commuting distances and has put the focus more exclusive on car travel. Eventually, all this has led to increased energy consumption. For the other main roads, which are traversing a structurally different socio-economic landscape, this finding does not apply. Overall, it seems that two types of roads can be identified using our framework. The first type of main road crosses an area with a fairly diverse economy, where the residential structure is to a large extent mixed with the job market. This is particularly true between Brussels and Antwerp (I11, I12), but also in a number of other places (I13–15). Moreover, all main road segments crossing the metropolitan areas, harbour and airport areas are of this type. The second type of main road runs through a relatively remote area, without providing a smooth connection with a major employment centre in the urban network of the Flemish Diamond. Examples of these corridors can be found in I16–20.

7.3. Relation to the access to the rail network

The link with the rail network is also very visible. Stations are located next to the historic centres, which have the highest residential density and often also the largest functional mix. Of the lower energy consumption for home-to-work travel that we often observe in the vicinity of the railway stations, only a tiny share can be attributed to the train commuters. This is explained in that the average train trip in home-to-work travel still represents an energy quantity of 70% of that of an average car commuting trip.

But the link is not unambiguous. A number of important rail lines are flanked by an – in terms of traffic volume – much more important motorway, which eventually leaves its heavy mark on local commuting behaviour. This is illustrated in the counter-urbanised area around J1, where good train and motorway connections are present. The energy consumption is thus high.

In the region southwest of Brussels (A1), a different phenomenon emerges. Despite good rail links with the Flemish Diamond and the absence of a main road, we find very high energy consumption levels. The census blocks in which the main stations are located, score a lot better in terms of energy than the surrounding areas. The blocks in the immediate vicinity of the Ghent's main railway station (J2) have a very large share of train commuters as well as relatively high energy consumption. Note that this station has a very good train connection to Brussels. Areas which manage to combine a large share of train commuters with low energy consumption in home-to-work travel are rare: J3–8 fall into this category.

8. Conclusions

We have argued that the energy performance of the transport system is an important approximate indicator for the sustainability of a spatial structure. This is certainly true when advocating a so-called low carbon economy is put increasingly higher on the political agenda. Obviously the link with the spatial or urban (re)development of cities should be made as well. Having a better understanding of the mechanisms that cause the major observed regional variations in energy consumption will lead to better land-use planning in practice.

The issue of proximity in planning remains very important. In home-to-work travel, the distance between home and workplace is to a very large extent determinant for the energy performance of the commuting system. Contrary to the conventional belief, the mode used is of much less importance. In this respect we notice a discrepancy with the current mobility policy of the Flemish government, which is very much focused on the reduction of the share of car drivers, but much less on a reduction of the number of kilometres, despite an increase by 10% of the average commuting distance between 1991 and 2001 (Verhetsel et al., 2007).

Hence, the opportunity for someone to find a suitable job nearby his or her living environment, or the ease with which someone can move in the vicinity of his or her work will increasingly determine the robustness of a spatial-economic system in a climate of rising oil prices. It appears that travel behaviour remains largely determined by the rigidity of the housing stock, which makes short term policy intervention not easy. This applies too – *mutatis mutandis* – for non-work related trips, although these show higher elasticities. Therefore, we argue that it is important to develop a more profound insight into the regional variations in the energy performance of the whole transport system. So we will get a better understanding of the

processes that led to the current situation, and we will be able to assess the policies that played a part or can still play a part in this. In this respect the development and implementation of a commute-energy performance index seems a useful indicator to assess both transport and spatial planning policies with respect to inducing sustainable development.

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